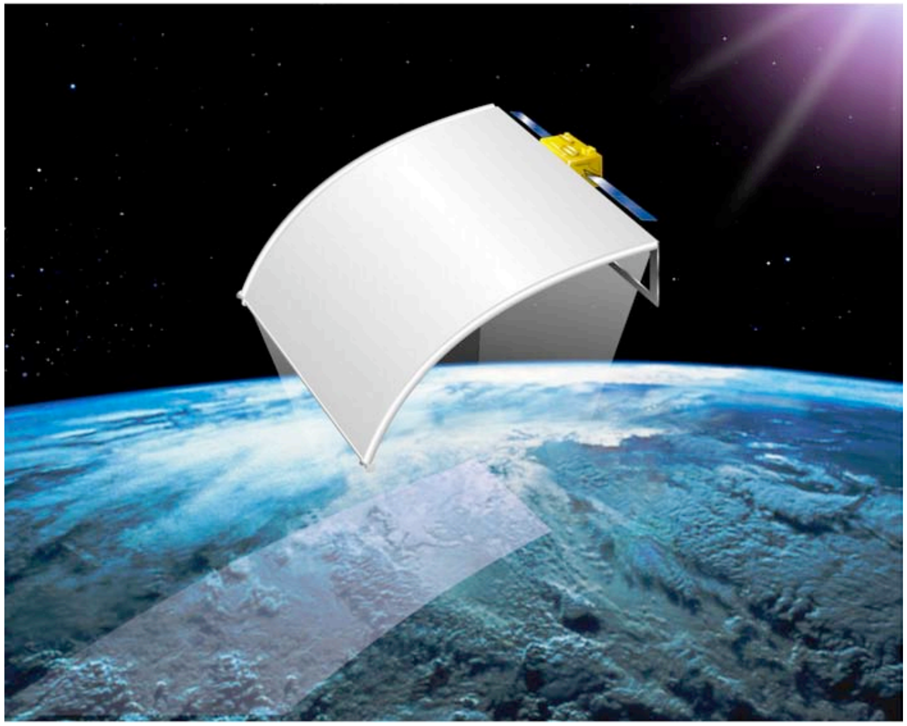
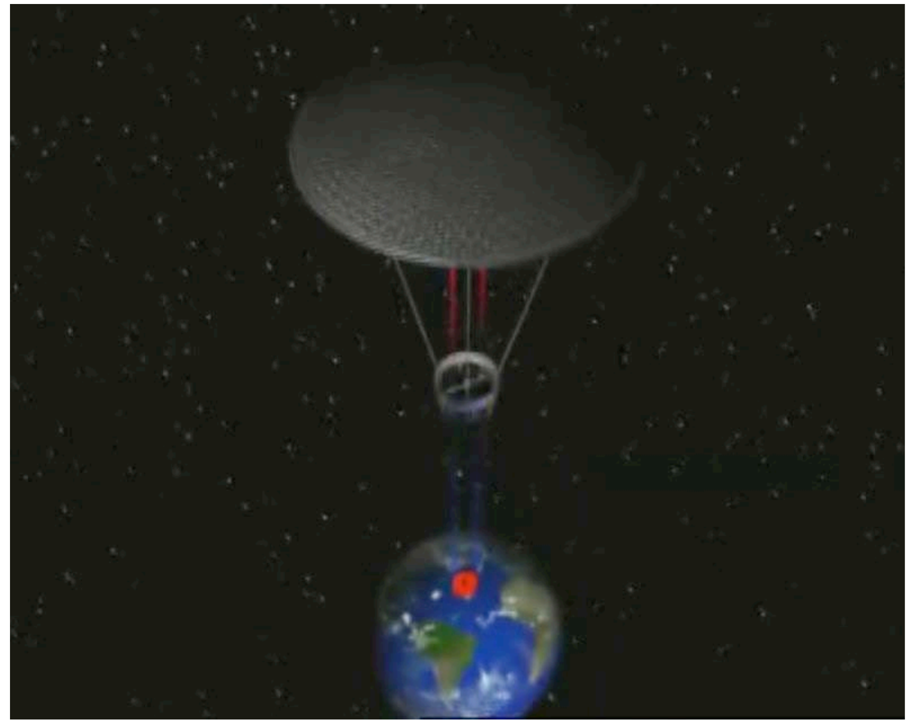
Spaceborne Atmospheric Radar Technology



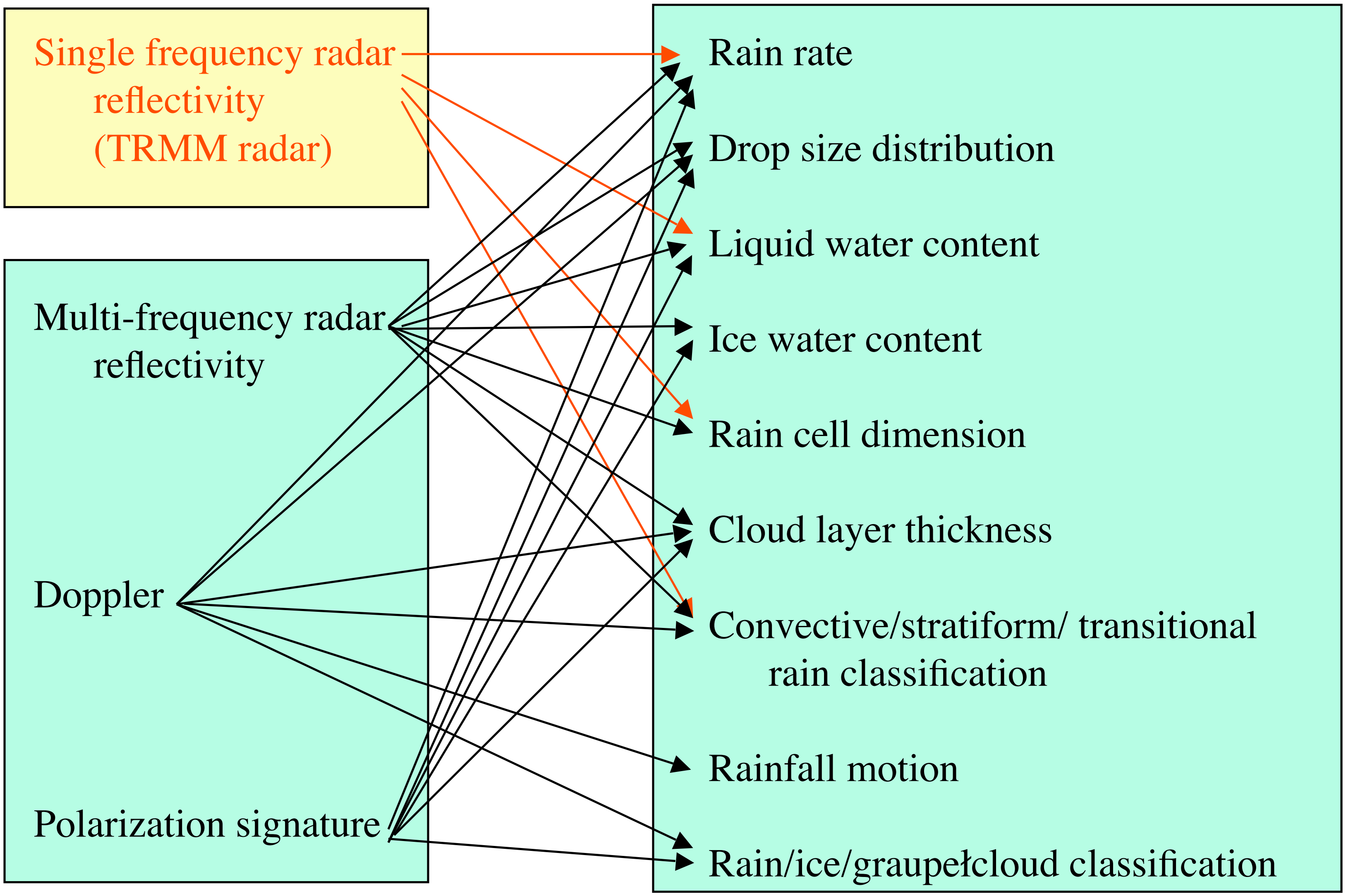


Eastwood Im and Stephen L. Durden

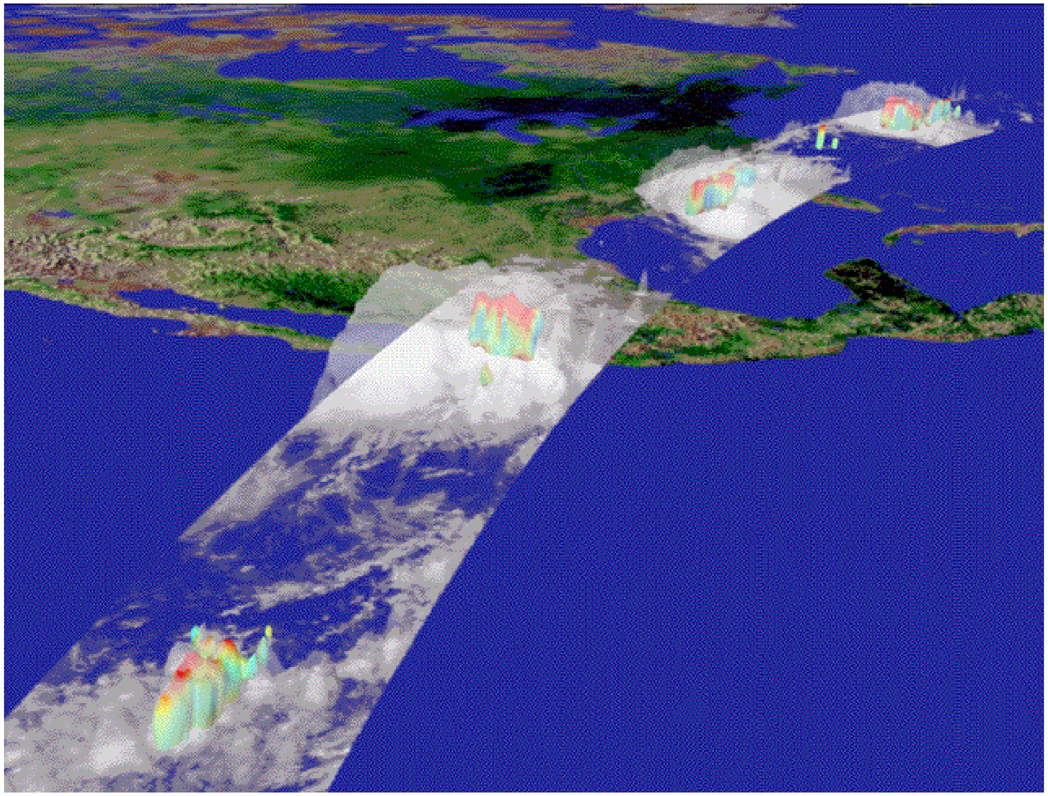
Jet Propulsion Laboratory

June 29, 2005

Radar vs. Atmospheric Parameters



TRMM Precipitation Radar - The Pioneer



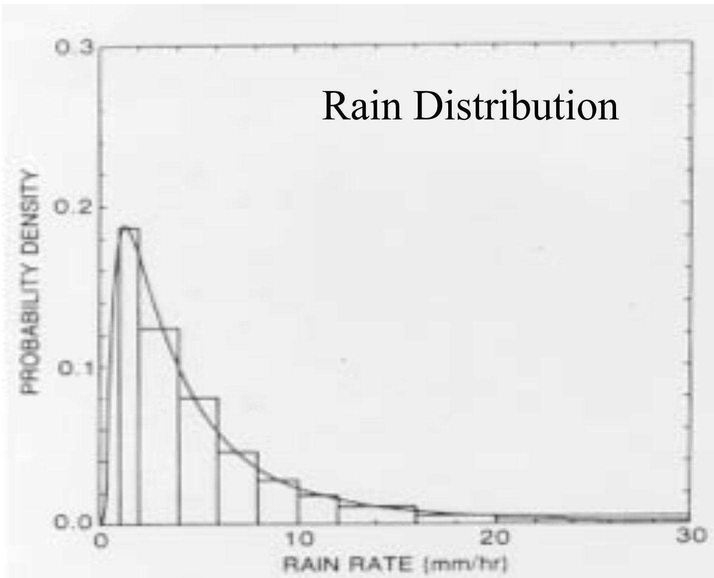
Tropical Storm Howard, Hurricane Isis, Hurricane Earl and Hurricane Danielle all line up under TRMM, passing over the scene from West to East on Sept. 2, 1998. (Courtesy of NASA/NASDA TRMM Project).

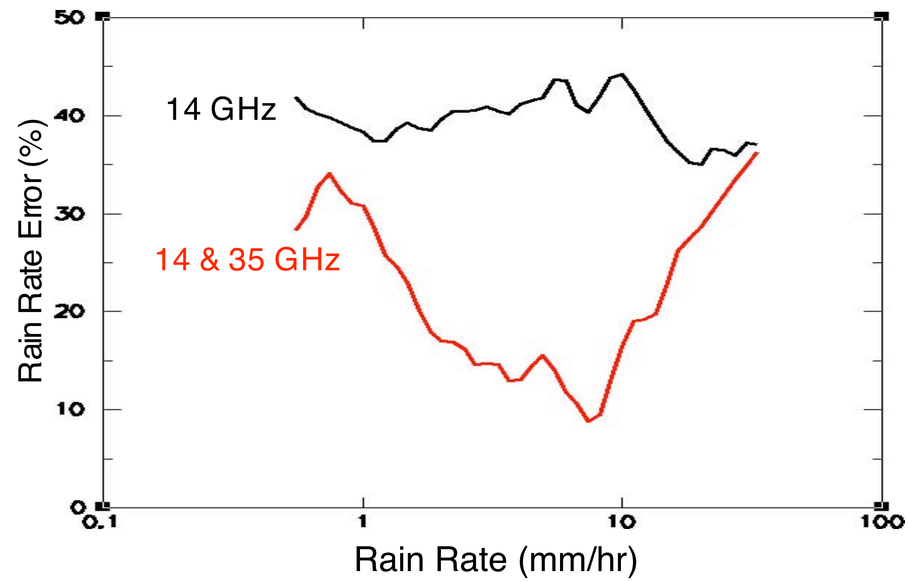
- TRMM satellite's primary rain sensing instruments
  - Precipitation radar
  - Multi-frequency radiometer
- TRMM orbit
  - ±35˚ inclination
  - 350 km altitude
- TRMM Radar characteristics
  - 14-GHz
  - 2-m antenna
  - Cross-track ±17˚ scanning
  - Reflectivity-only measurements
  - Radar mass: 465 kg
    - Slotted waveguide phase-array antenna weighs >300 kg
- TRMM instruments have made significant observations
  - Climate research
  - Weather prediction

Future Spaceborne Rain Radar Considerations

- Incorporate dual-frequency (14/35 GHz)
  - Measure parameters in drop size distributions
  - Improve rain rate measurement accuracy
- Increase the antenna size to increase horizontal resolution
  - Reduce beam-filling induced measurement bias
  - Reduce vertical smearing and surface clutter contamination
- Incorporate adaptive scan to increase swath coverage without reducing the number of independent samples per resolution cell
  - Reduce sampling error
  - Increase revisit frequency
- Add Doppler capability to measure vertical rainfall motion
- Add dual-polarization capability to detect hydrometeors in mix-layer
- Use digital chirp generation and on-board pulse compression to improve rain detection sensitivity
- Incorporate build-in flexibility on radar parameters, timing and control to allow radar to be “re-programmed” for different mission needs
- Reduce radar mass to reduce mission costs

Rain Retrieval Accuracy Improvement w/ Dual-Freq Radar

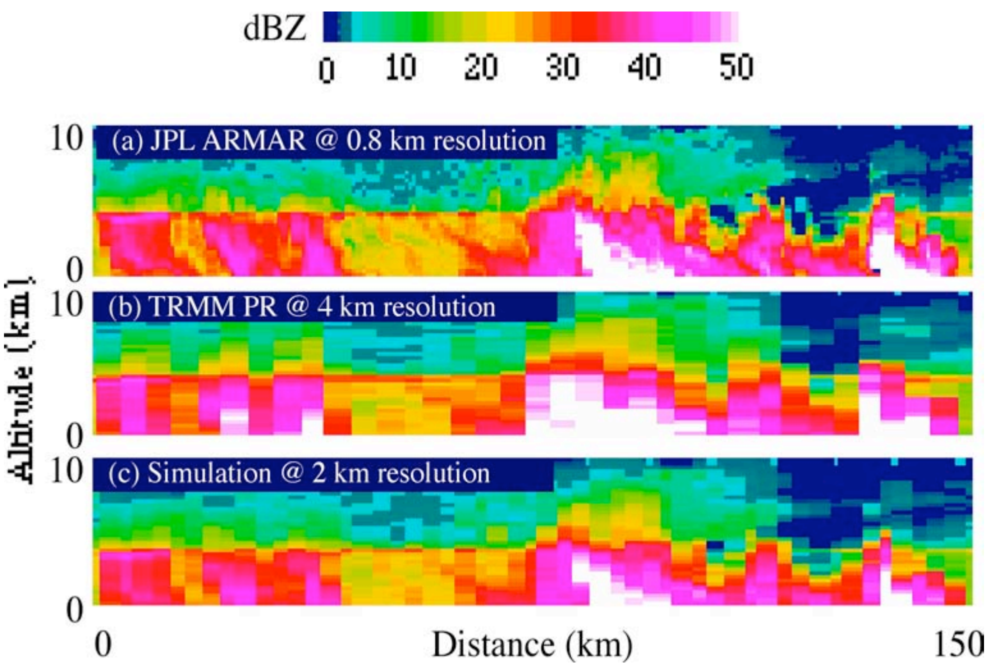




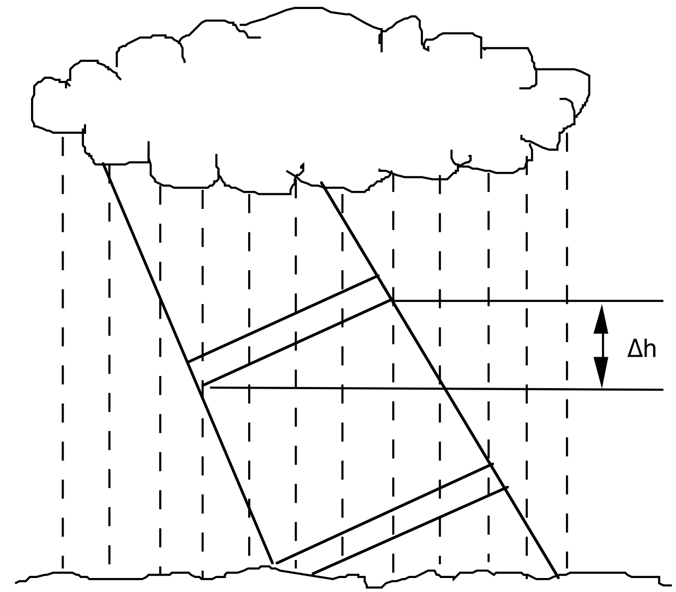
- **Over 90% of global rainfall are less than 10 mm/hr**
- **Dual-frequency radar can improves rain rate retrieval accuracy between 25% to 200% in this rain region**

- **Requires 2 frequencies at matched beams**

Beam Filling and Resolution Considerations



- Resolution improved from 4.3 km to 2 km can reduce bias by as much as 40%
- Requires twice the antenna size and 4 times the amount of data (as compared to TRMM PR)

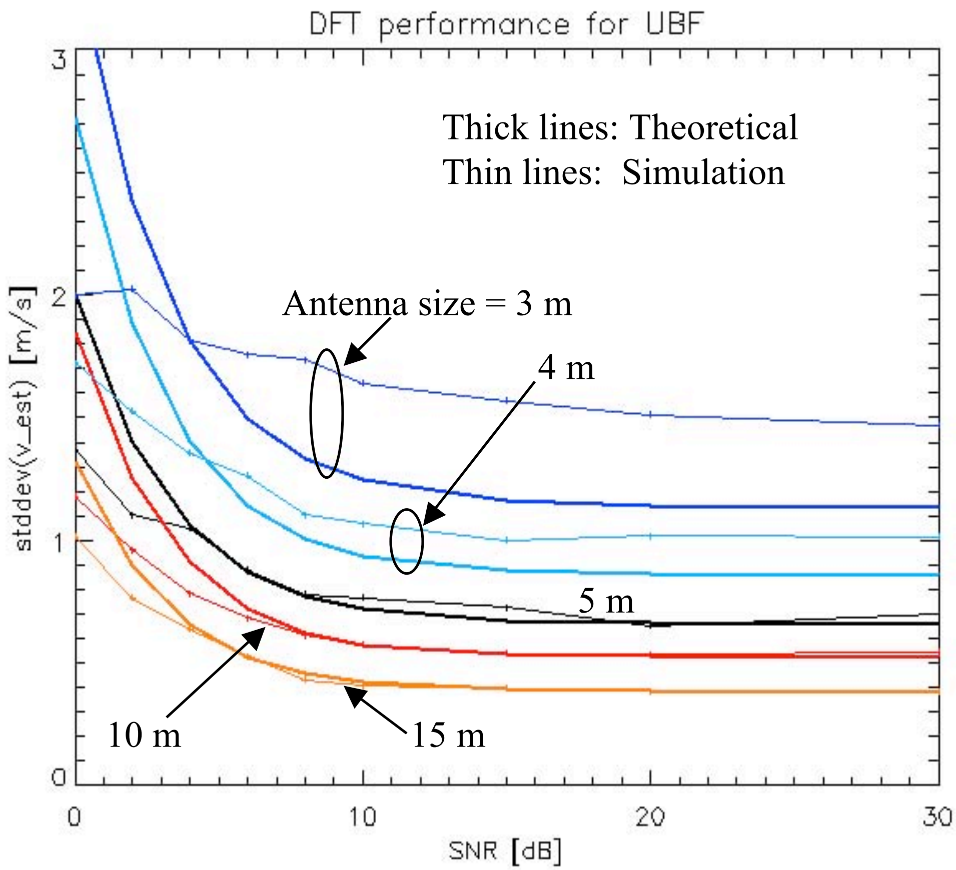


- At off nadir, radar measurements are affected by vertical smearing (Δh) and surface clutter
- At 17°, TRMM radar altitude and horizontal resolution, Δh ~ 1.5 km
- Height of stratiform rain cells
  - 3 -5 km depending on latitude
- Antenna smearing effect is inversely proportional to antenna size

Doppler Measurements Considerations

- Vertical rainfall velocity is important for cloud modeling, latent heat measurments, and for understanding rainfall processes and dynamics
- Velocity accuracy requirement : 1 m/s
- The Doppler spectral width is inversely proportional to antenna size

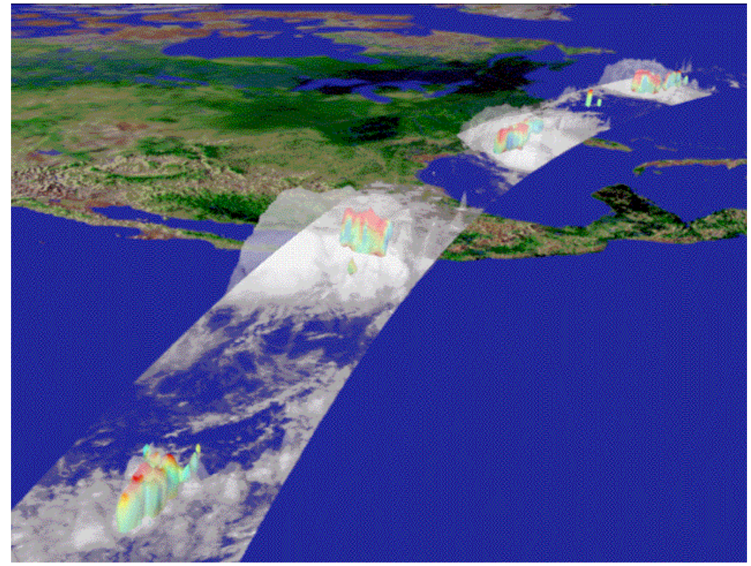
- For homogeneous (uniform) rain, our simulation shows that the antenna size required is at least 4-m
- For inhomogeneous rain, the requirement is tighter



Scanning and Global Sampling Consideration

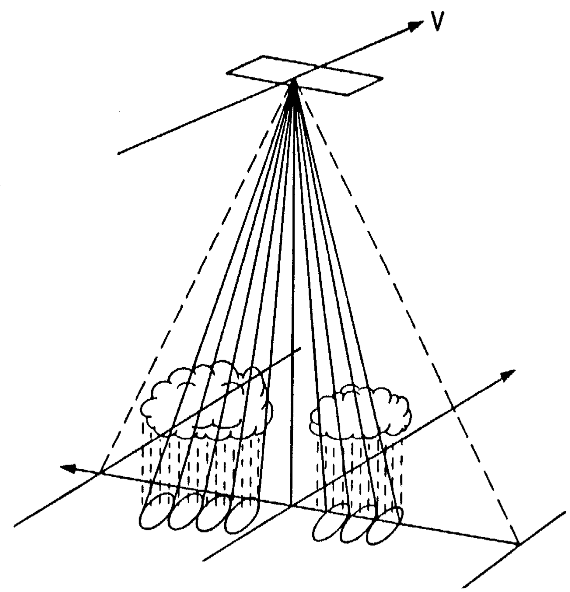
Conflicting Requirements:

- Reducing sampling bias in monthly rain rate
  --> large scan
- Minimizing radar dwell time
  --> narrow scan
- Not wasting resource
  --> scan over rainy areas only



Solution:Adaptive Scan (proposed by D. Atlas in 1980's)

- A rapid scan of a large swath (large scan)
- Find raining regions and dwell on them only (adaptive scan)
- Technology needs:
  - Fast sorting algorithm
  - Fast real-time computation/processing/selection



Peak Power Limit and Pulse Compression Considerations

- TRMM Precipitation Radar uses short pulse to obtain vertical resolution of 250 m
  - Requires high peak power (800 W)
  - 64 independent samples per resolution cell (per 35° scan swath)
- Future rain radar desires to have large swath, but maintain at least same number of independent samples
- Pulse compression techniques can resolve the inherent problems of short-pulse approach

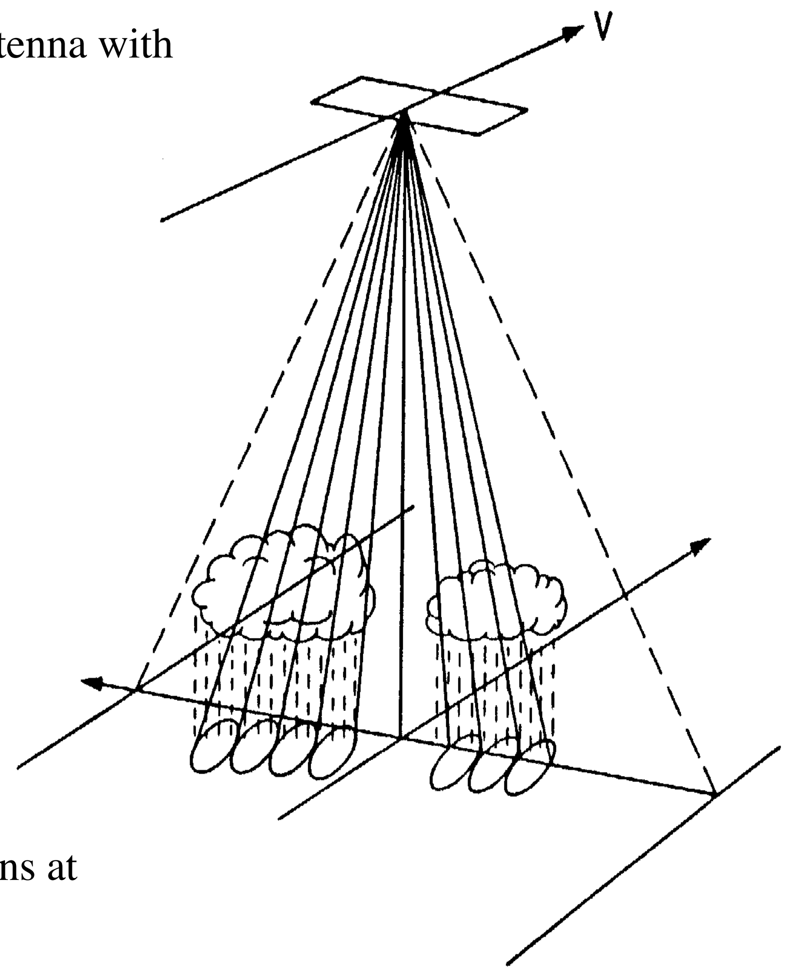
	Peak Pwr (W)	Pulse length (μsec)	Bandwidth (MHz)	PRF	Ave. Pwr (W)	Vert. Res (m)	Number of Samples	SNR (dB)
Short Pulse	1000	1.67	0.6	2000	3.3	250	80	X
LFM Pulse 1	20	83	0.6	2000	3.3	250	80	X
LFM Pulse 2	20	83	1.2	2000	3.3	125 250	80 160	X X
LFM Pulse 3	100	83	0.6	2000	16.6	250	80	X+7

- Challenge: Pulse compression sidelobe levels for detecting 1 mm/h rain rate near surface:
  - -60 dB @ 14 GHz; -53 dB @ 35 GHz.

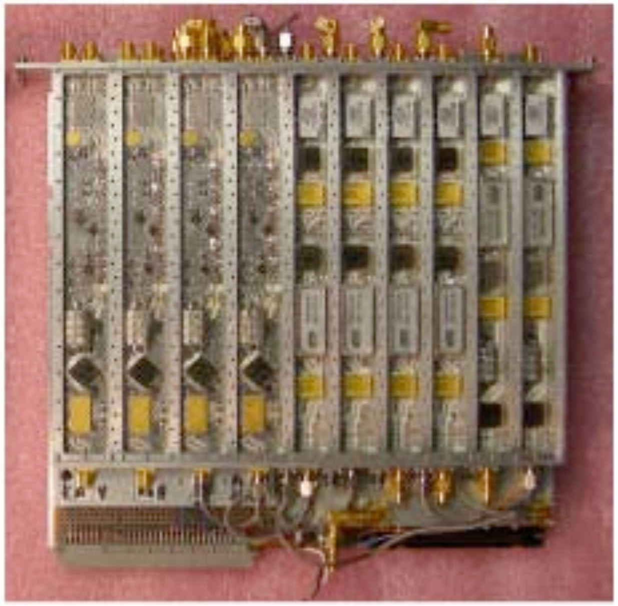
- **Requires:**
  - **Accurate control of gain and phase errors**
  - **Real-time pulse compression**
    - **Substantial processing speed**

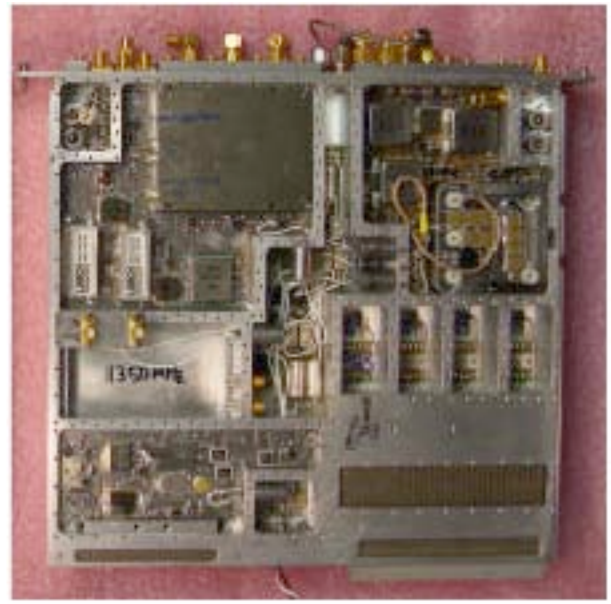
Notional 2nd-Generation Rain Radar Concept

- 14 GHz (Ku-band) and 35 GHz (Ka-band) dual-frequency radar
- Large, lightweight, deployable, dual-frequency antenna with matched beams:
  - 5.3m×5.3m @ 400 km altitude
  - Horizontal resolution: 2 km @ h=400 km
- Wide-swath coverage using adaptive scanning
  - ± 37˚scan, 600 km swath at h=400 km
- Doppler measurements if rain detected at nadir
- Simultaneous HH and HV polarization
- On-board, real-time pulse compression
  - 250 m vertical resolution
  - Reduced transmit power required:
    - 200 W @ 14 GHz; 50 W @ 35 GHz
  - Enhanced minimum detectable Z:
    - 10 dBZ @ 14 GHz; 5 dBZ @ 35 GHz
- Programmable radar parameters to allow operations at different altitudes
- On-board processing: Doppler, pulse averaging



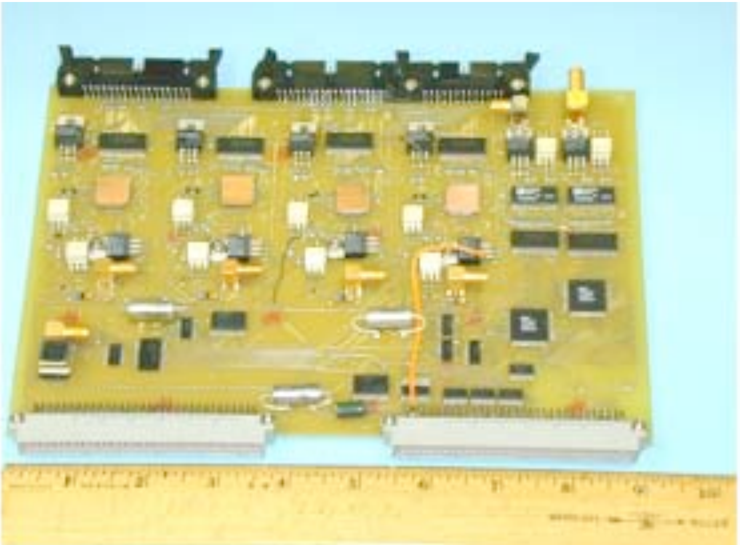
LO / IF Module

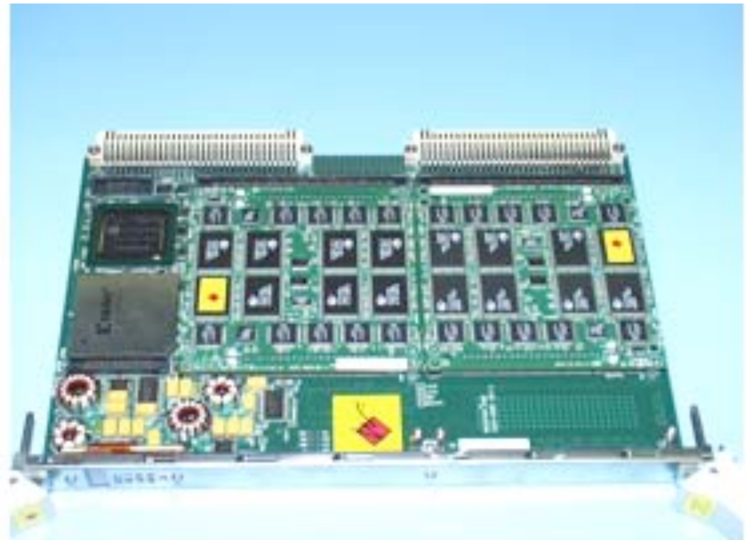




- All RF components operating below 10 GHz
    - Two transmit channels (14-GHz H-pol; 35-GHz H-pol)
    - Four receiver channel (14 GHz H-pol and V-pol; 35-GHz H-pol and V-pol)
    - 10 MHz MO, 40MHz LO, 1350 MHz LO, 1360 MHz LO
- Designed for space flight
    - Compact (23 cm x 20 cm x 4.5 cm) and fits in 2 VME card slots
    - Light weight (3.6 kg)
    - Excellent EMC characteristics with thorough subcircuit shielding
    - Conduction cooled
    - Easy access for serviceability and reconfiguration

Key Digital Subsystem Hardware



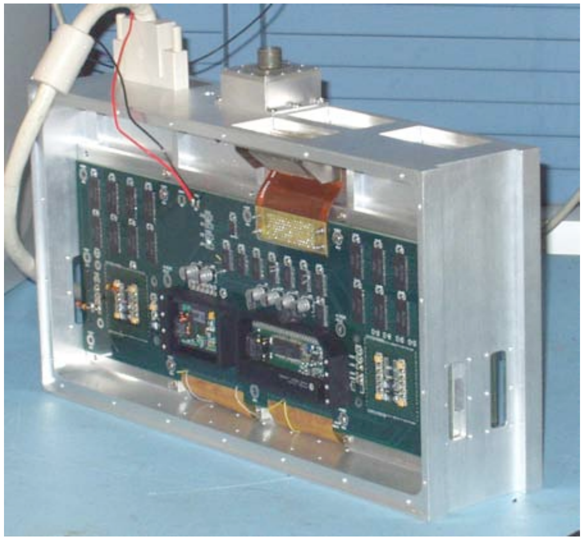


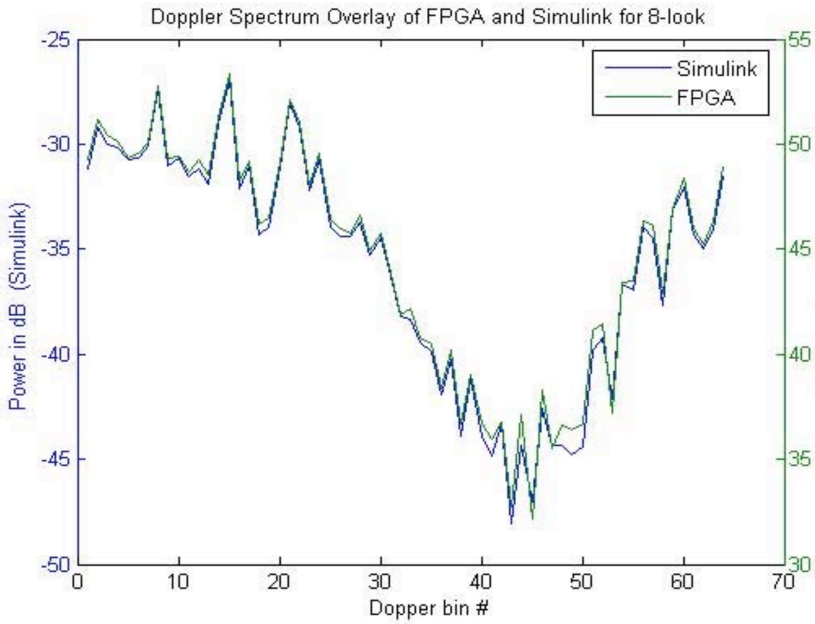
- ADC/AWG
  - 12- bit ADC and Variable Waveform (AWG) Generator cluster.
  - ADC oversamples 2 times for improved sample filtering
  - AWG includes pre-distortion function to reduce pulse compression sidelobe

- FPGA-based Data Processor
  - Real-time processing
    - Adaptive scan
    - Pulse compression
    - Pulse-Pair Doppler processing
  - Double buffer
  - Computer power:
    - 20 billion multiplications
    - 20 billion additions

FPGA-Based Real-Time Doppler Spectral Processor

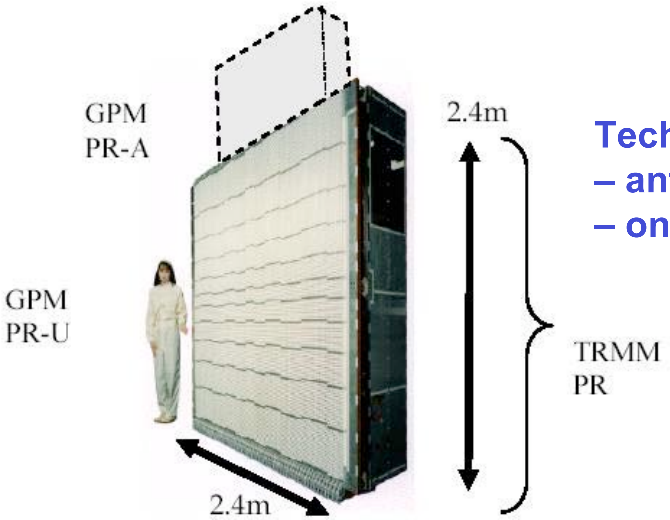
- Standard pulse-pair Doppler processing should work well for situations with uniform reflectivity within the radar beam; for non-uniform filling, biases may occur.
- These biases can be substantially reduced if the full Doppler spectrum is available; a processor has been designed to produce full Doppler spectra from complex input.
- The processor operates on 64 complex pulses, producing the Doppler spectrum at each of 480 range bins; it averages 8 spectra in range, providing 60 Doppler spectra.
- It has been developed in Verilog. Initial testing in a custom board using Xilinx parts (below, left) has been accomplished. The output spectrum compares well with a computer-calculated spectrum for the same data (below, right).



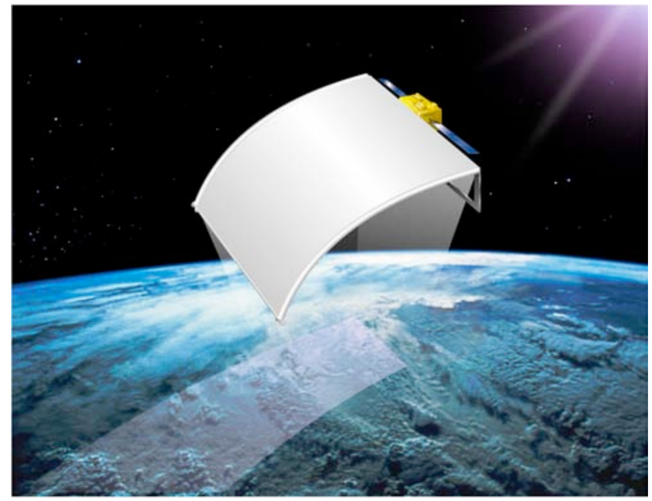


2nd-Generation Precipitation Radar Antenna Technology

(from D. Everett et al., 2002)



Technology breakthroughs:
– antenna
– on-board processing



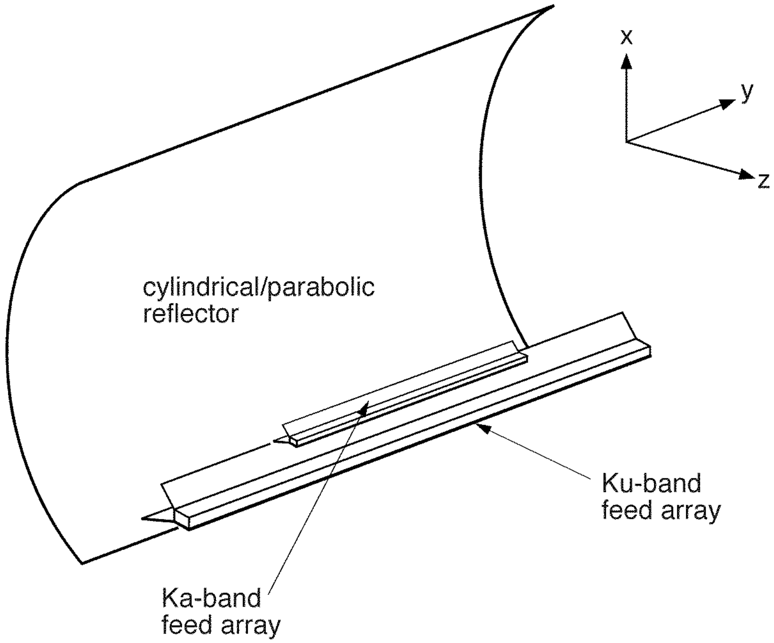
GPM Dual-Frequency Precipitation Radar (DPR)

- 2.4×2.4 m antenna aperture
- conventional slotted waveguide array
- 5 km horizontal resolution
- 200 km scan swath
- ~ 450 kg

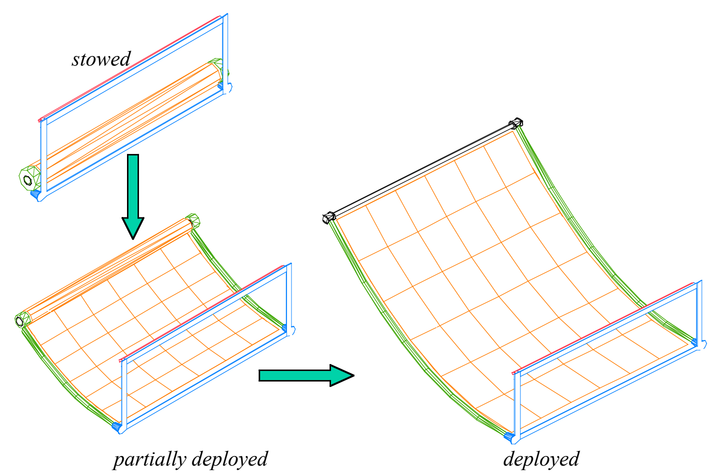
Second-Generation Precipitation Radar (PR-2)

- 5.3×5.3 m antenna aperture
- Membrane reflector with linear array feed
- 2 km resolution
- 500 km scan swath
- ~120 kg

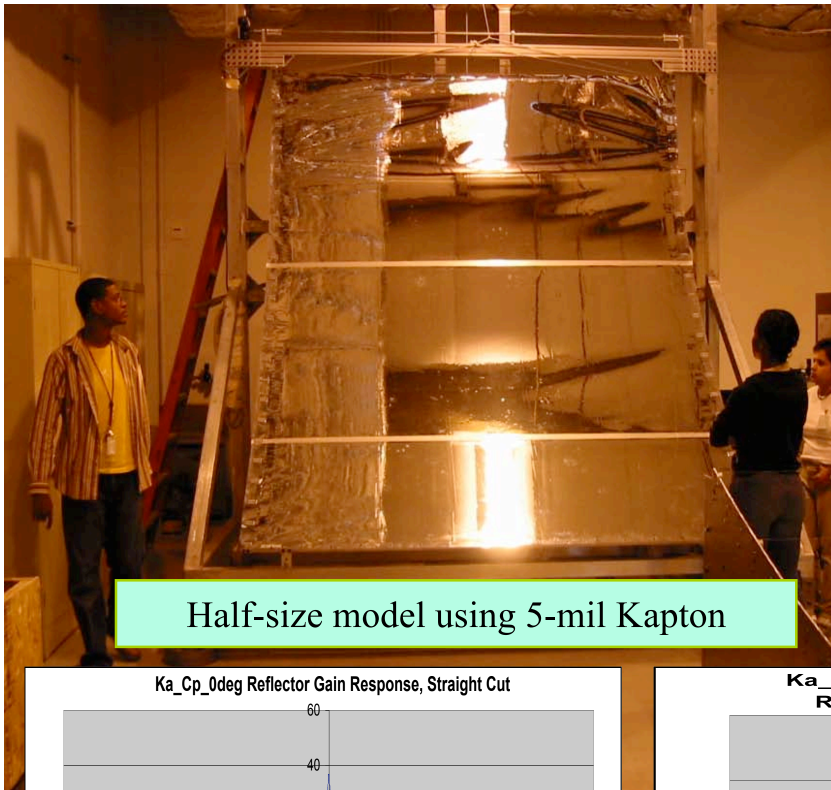
2nd-Generation Precipitation Radar Antenna Technology



- 5.3 m x 5.3 m aperture
- Dual-frequency array feeds
- Matched beams at 2 frequencies
- ± 37 deg scanning
- 55 dBi gain
- -30 dB sidelobe level
- Required 0.17mm RMS surface accuracy
- Estimated mass: 120 kg (~ factor of 3 improvement)

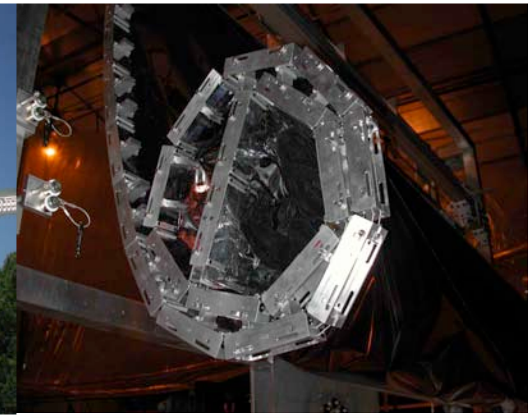


PR-2 Antenna Half-Size Technology Prototype Model

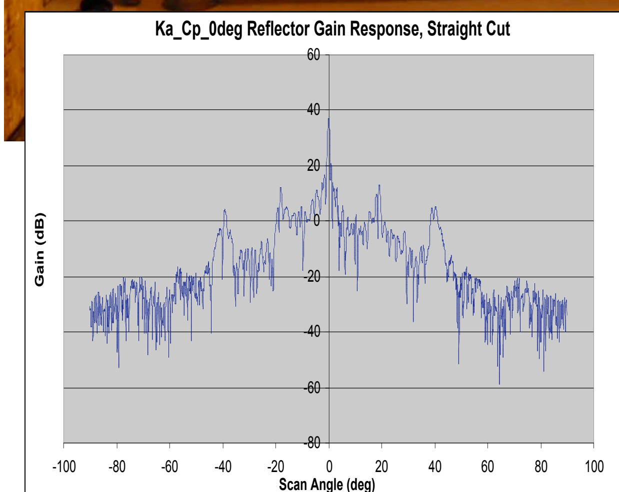


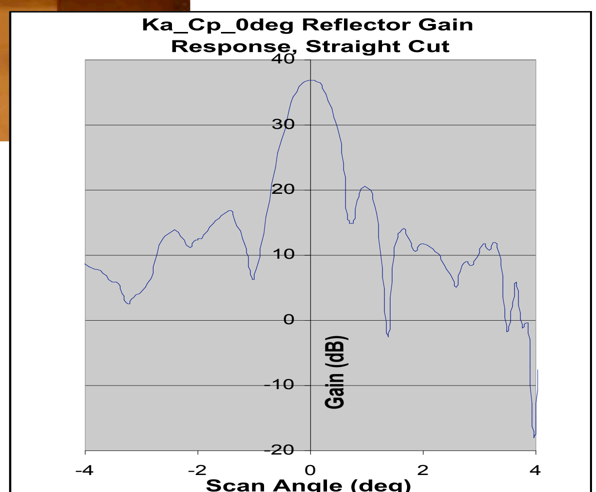
Half-size model using 5-mil Kapton

14-GHz antenna feed array



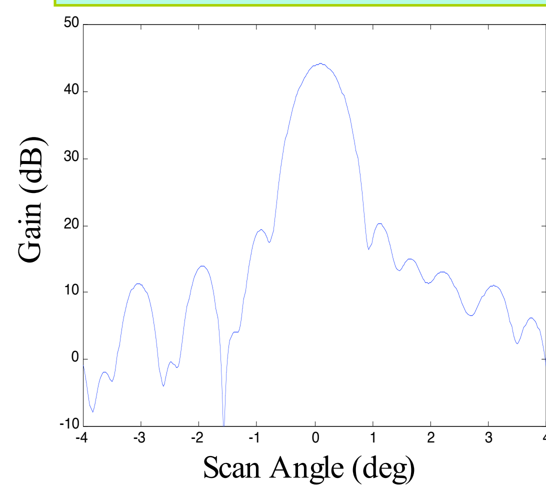
Antenna deployment





35-GHz pattern (measured)

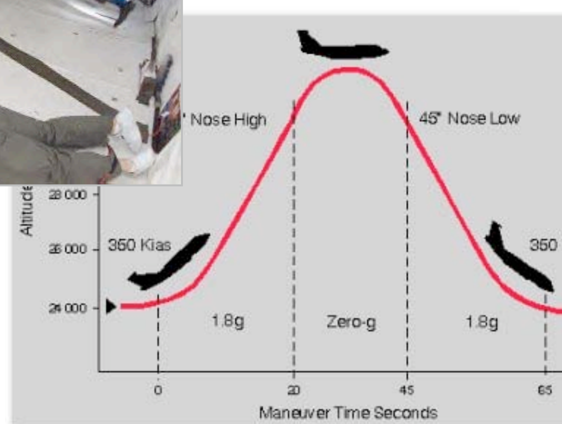
35-GHz pattern (simulated based on metrology measurements)

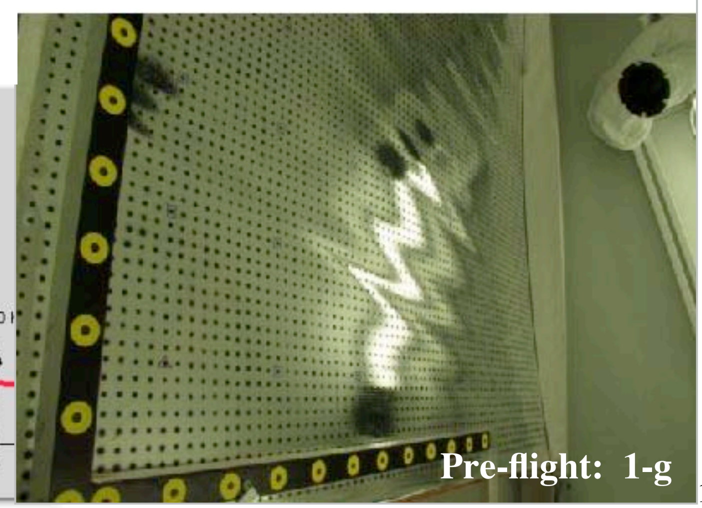


Antenna Sidelobe Issues and Solutions (1)

- **Measured antenna sidelobes were higher than desired due to larger antenna surface RMS error - Required: 0.17 mm; Measured: 1.1 mm**
  - Gravity-induced sag during ground test
  - Reflector surface ripples
- **Gravity-induced sag investigation and solution:**
  - Conducted reduced-gravity experiment with University of Kentucky in KC-135 aircraft
  - Sag significantly reduced
  - Factor of 2 reduction in RMS surface error

In-flight: ~0-g



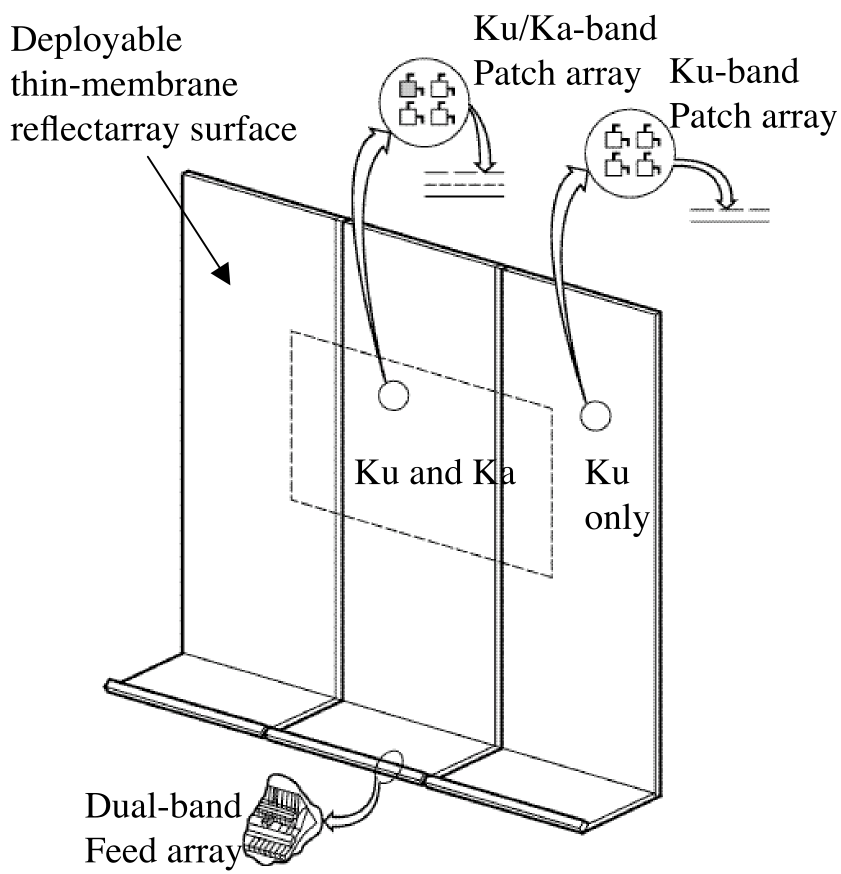


Pre-flight: 1-g

Antenna Sidelobe Issues and Solutions (2)

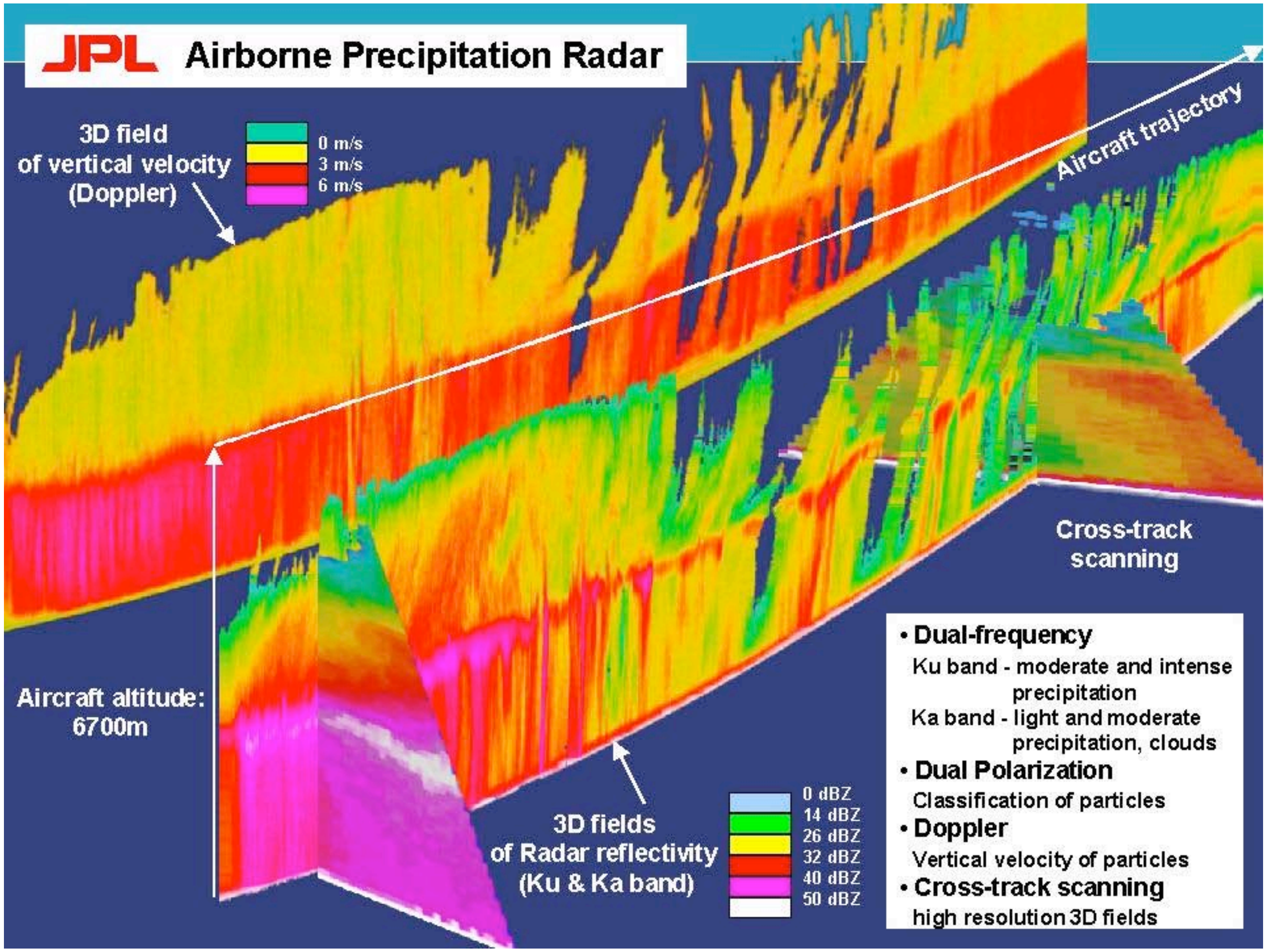
- **Surface ripple issue**
  - Caused by thin membrane (5-mil Kapton) boundary interface to frame structure

- **Solutions (in progress):**
  1. Use thicker membrane (10-mil Kapton)
  2. Use fiber-reinforced membrane
  3. Use fiber-reinforced membrane



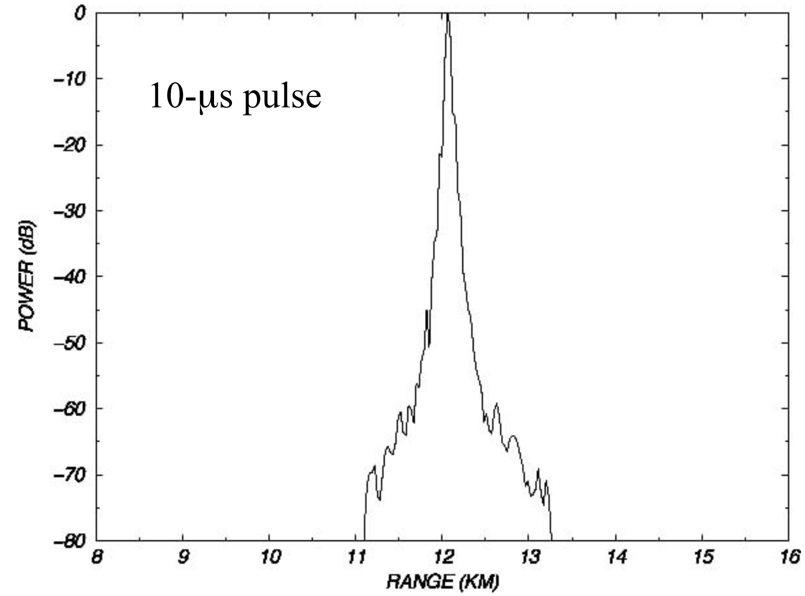
Airborne PR-2 Simulator

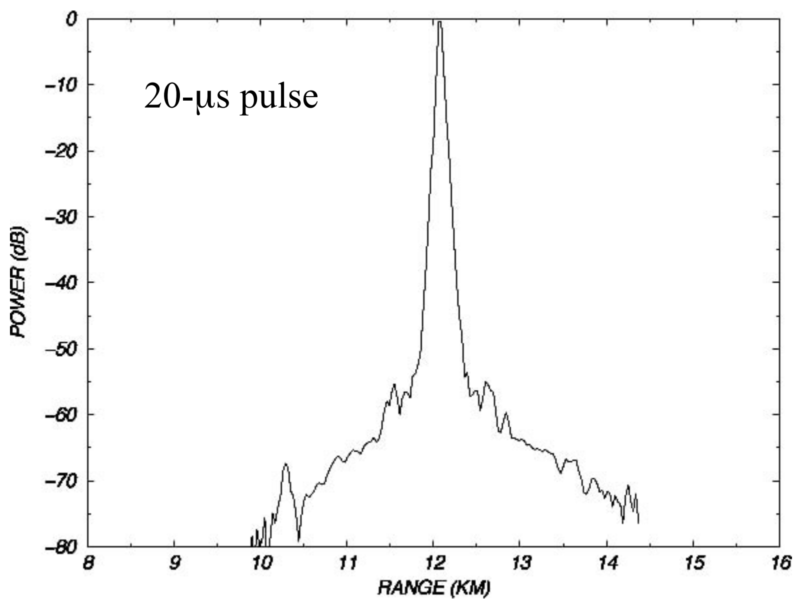
- PR-2 LO/IF module, real-time pulse compression and digital processing module were prototyped as airborne simulator, and flown on:
  - NASA DC-8: CAMEX-4 in 2001 and GPM DPR/LRR Experiment in 2003
  - NASA P-3: EOS AMSR-E Underflight (Wakasa Bay) Experiment in 2003.

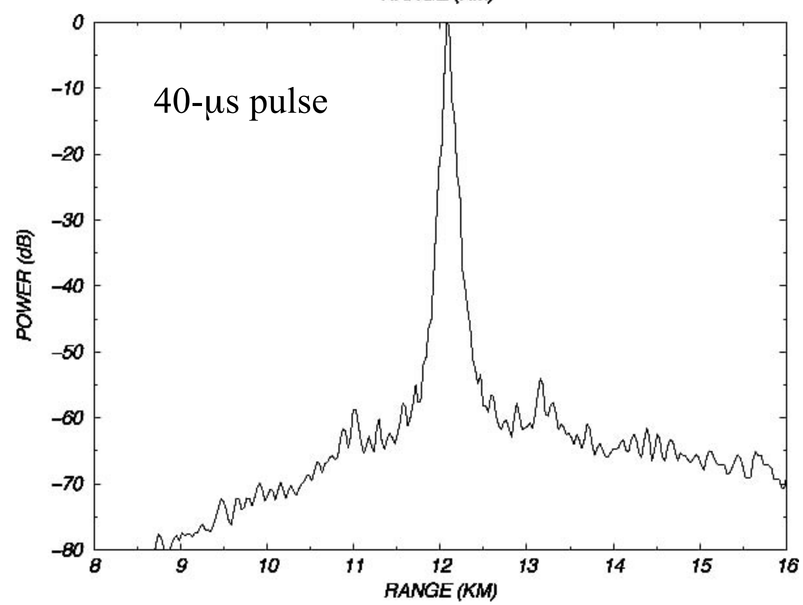


Airborne Demonstration of PR-2 Pulse Compression

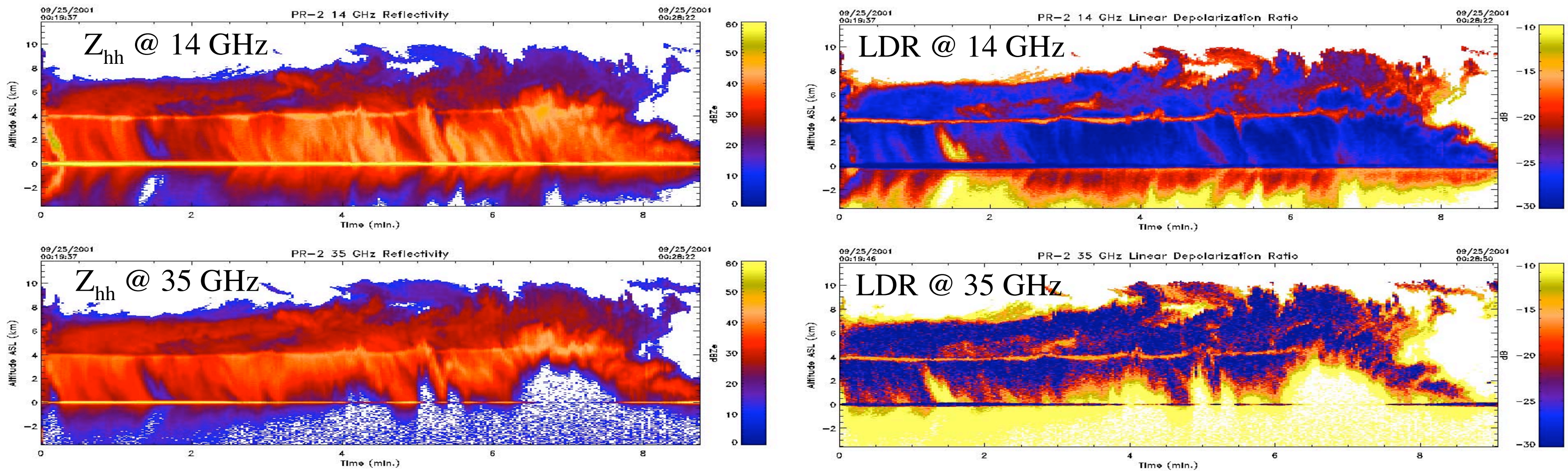
- 7/01 NASA DC-8 demonstration flights has demonstrated that the PR-2 indeed achieves the 60-dB sidelobe suppression capability
  - Use ocean as a reflector
  - Individual pulse returns from rain-free clear ocean captured
  - Averaging 80 pulses in time domain per sampling design
  - Test for various pulse widths

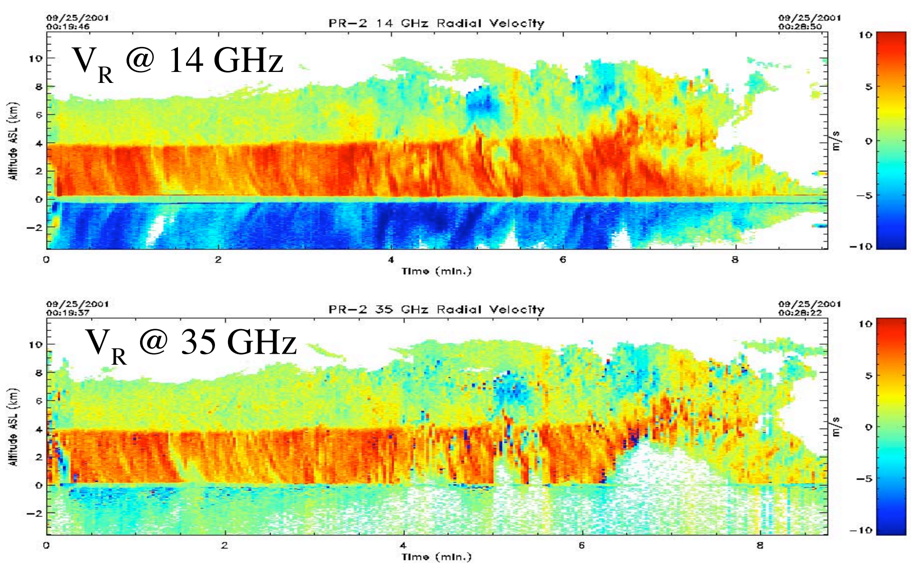






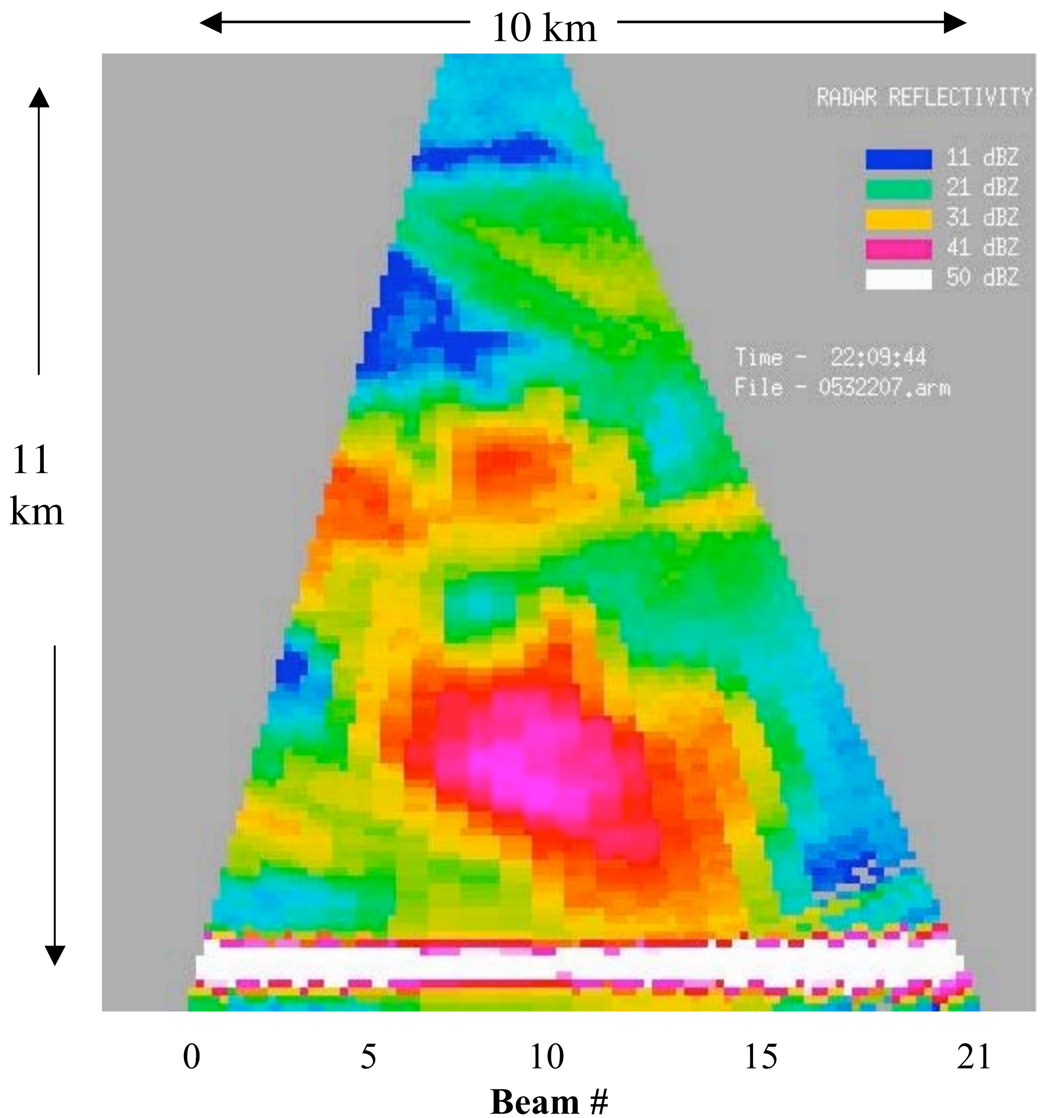
Measurements of Tropical Cyclone Humberto by Airborne PR-2 Simulator





- Airborne prototype of 2nd-generation technology model participated in the 4th Convection and Moisture Experiment (CAMEX-4) in Aug-Sep 2001
- Acquired multi-parameter rain data of on hurricane, several tropical storms, and many isolated rain cells
- Data are being used for science studies and space-based algorithm development

Airborne Demonstration of PR-2 Adaptive Scan



beam

10 ←"best"
9
11
8
12
7
6
5
13
14
4
3
15
2
1
0
16
17
18
20
19 ←"worst"

Algorithm

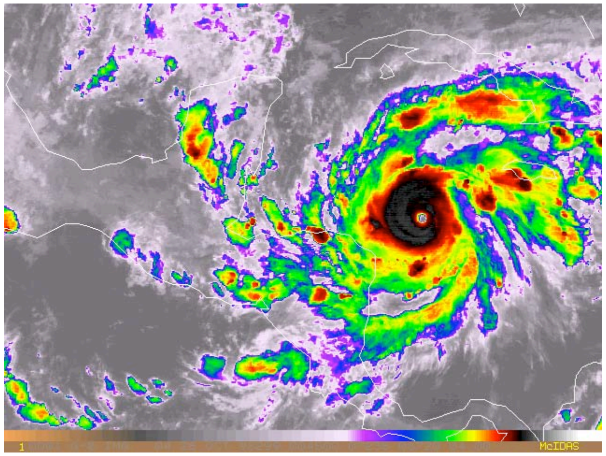
- Algorithm automatically finds surface
- Computes rain reflectivity in each cell
- Compares reflectivities and reflectivity gradients of entire beam against pre-set criteria
- Ranks individual beams in each scan

Algorithm Verification

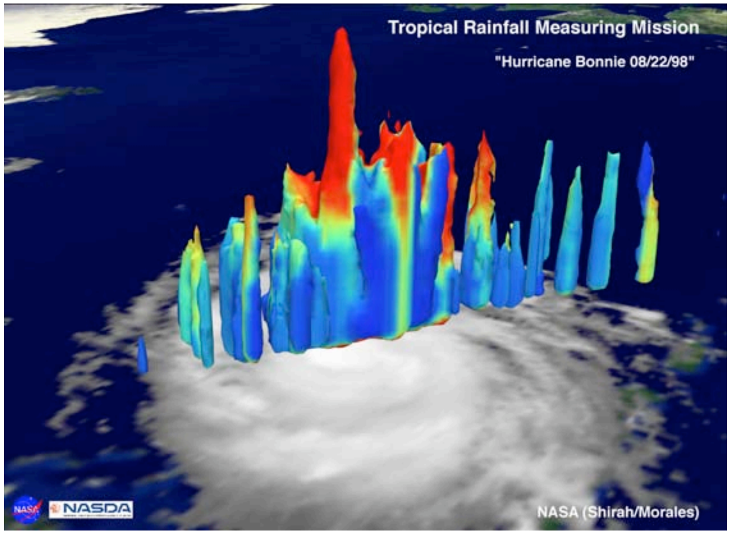
- Repeat above procedure for hundreds of radar scans to verify algorithm performance
- Success rate over 98%

Geostationary Earth Orbiting Radar for Hurricane Monitoring

- **Extension of PR-2 Technology:**
  - 35-GHz PR-2 instrument electronics technologies can be applied for GEO radar to monitor hurricanes and severe storms
- **Instrument Objectives:**
  - Measure hurricane rainfall intensity, dynamics, and life cycle for improved model prediction of track, intensity, and rain rate
  - Provide data for improved prediction of hurricane-induced floods
- **Practical Benefits:**
  - Life saving and enhanced public safety
  - Improved emergency response capability and reduced false-alarms
  - Optimized emergency resource utilization and cost benefits
  - Benefits to other economic sectors (e.g., insurance coverage…)

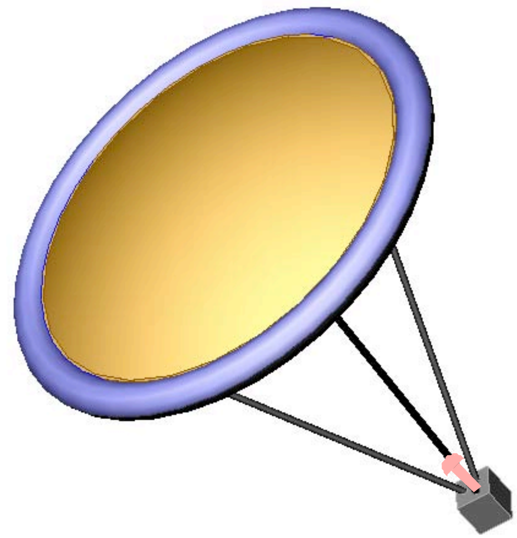


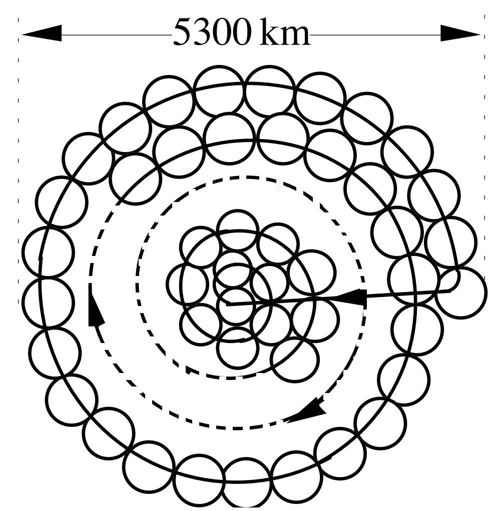
- **Radar Advantages**
  - Penetrate all clouds
  - 3-dimensional profiling critical parameters and dynamics which control and/or determine the hurricane formation and evolution
    - Rain intensity
    - Vertical motion
    - Cloud process
    - Latent heat release



GEO Hurricane Monitoring Radar: Concept and Innovations

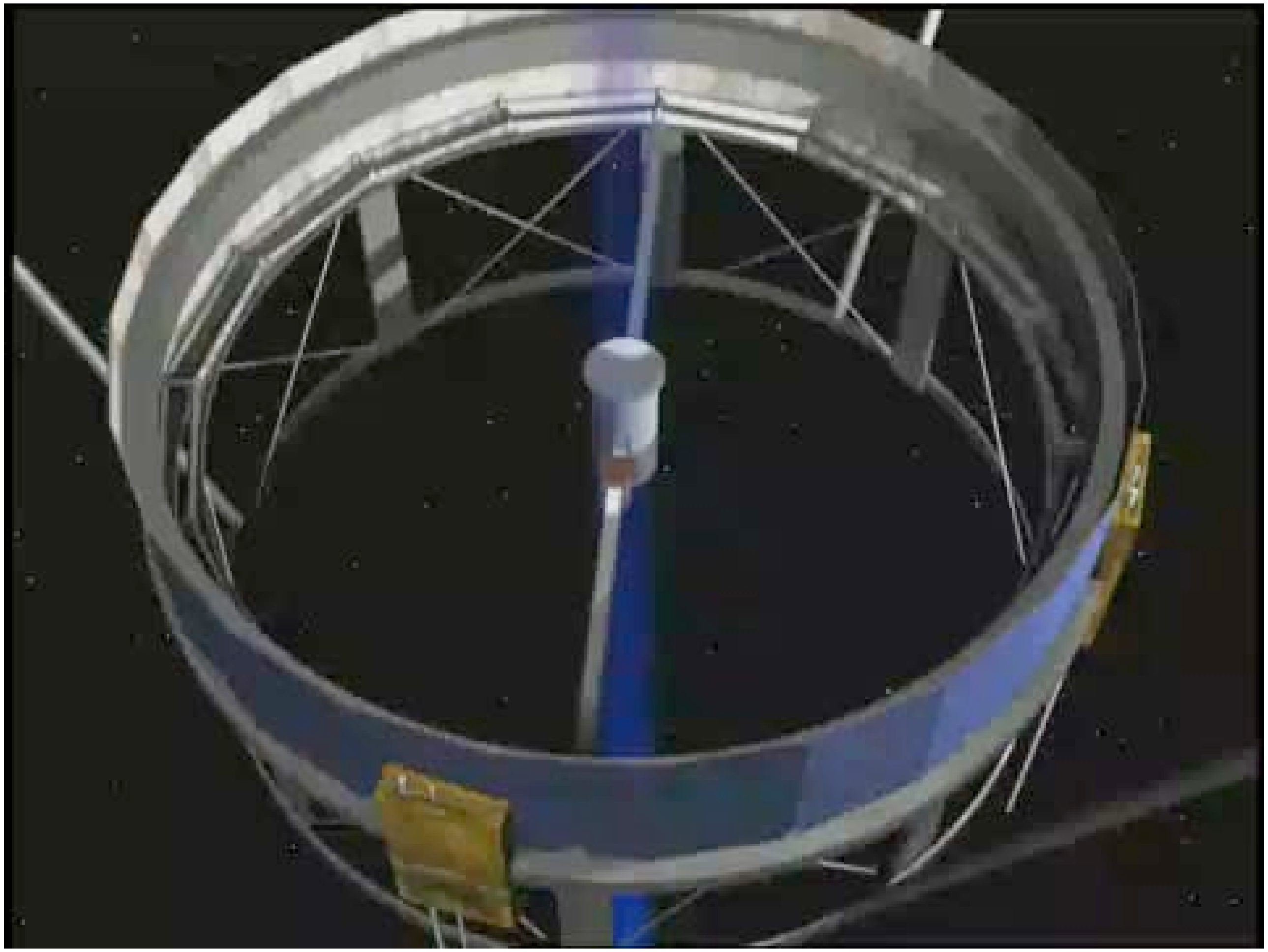
- Operating in geostationary orbit (alt. = 36,000 km)
- 35-GHz, 4° spiral scanning radar to cover 5300-km diameter earth disk (equivalent to coverage of 48° latitude and 48° longitude)
- Deployable, 35-m diameter spherical aperture antenna to obtain 12 to 14 km horizontal resolution
- Innovative antenna scan strategy:
  - 1 transmit feed and 1 receive feed with fixed spacing to compensate for pulse delay
  - Scan by motion of 2 feed sets on spiral path
    - Advantage over 2-D electronic scan, which requires millions of phase shifters
    - Advantage over mechanical rotation of entire antenna, which creates unacceptable torque
    - Advantage over S/C rotation, which requires custom-made, usually very expensive S/C
- Vertical resolution of 300 m using pulse compression
- Rain detection sensitivity: ~ 5 dBZ (after 100 sample averaging)
  - ~12 dB more sensitive than the TRMM radar
- Vertical Doppler profile measurements with 0.3 m/s precision
- One 3-D full-scan image once per hour
- Real-time processing to reduce downlink data volume/rate





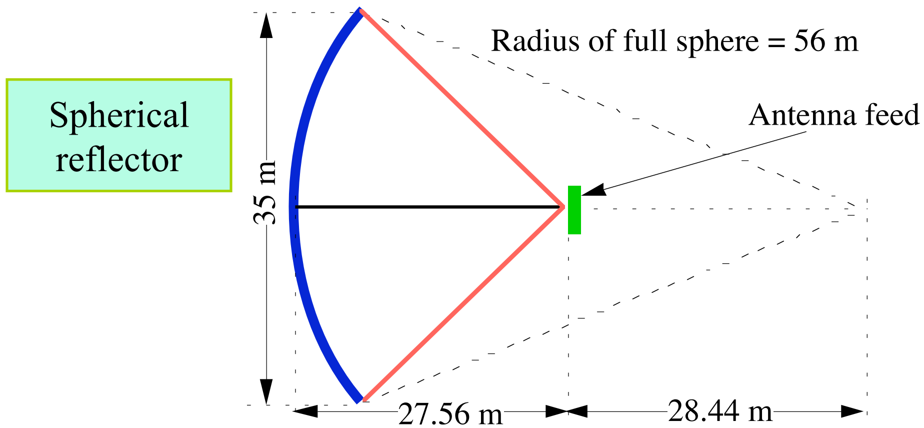
Scan pattern

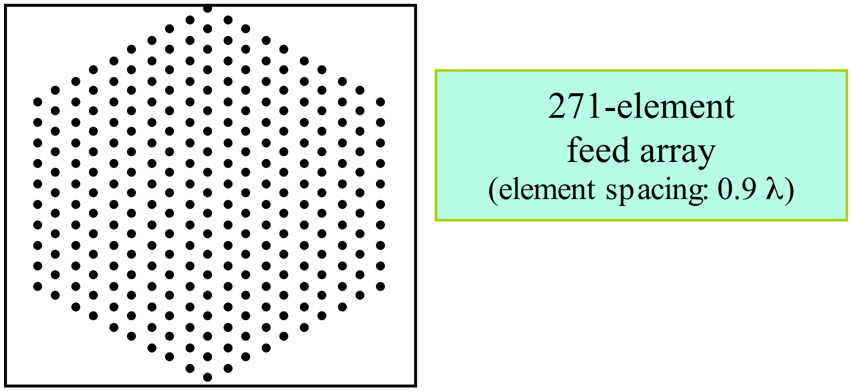
GEO Hurricane Radar Observation Concept: An Illustration

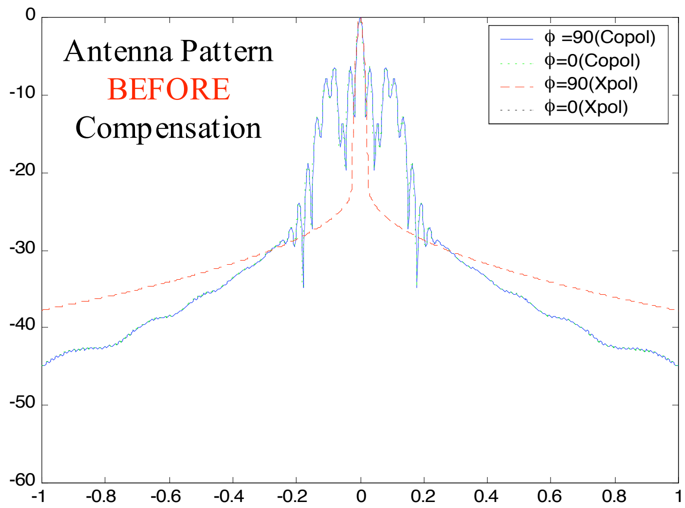


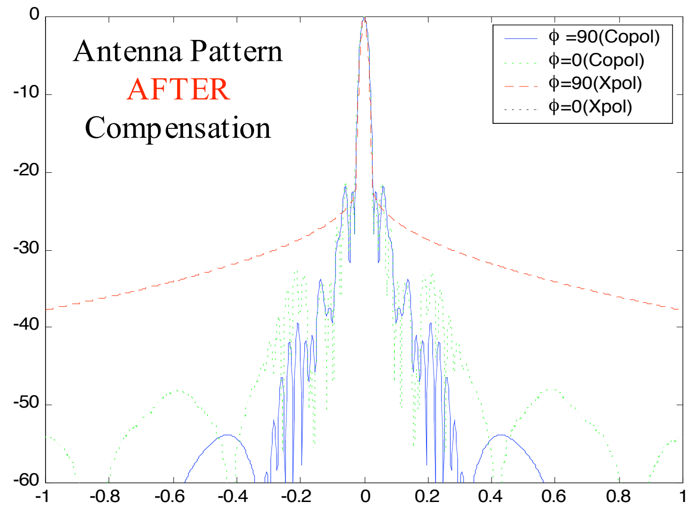
GEO Hurricane Monitoring Radar: Antenna Design

- Spherical antenna reflector allows 2-dimensional scan with minimum degradation
- 271-element feed array with designed phase distribution to compensate for spherical aberration.
- 28 m aperture, larger physical size to allow for scanning (35 m), F/D of ~ 1







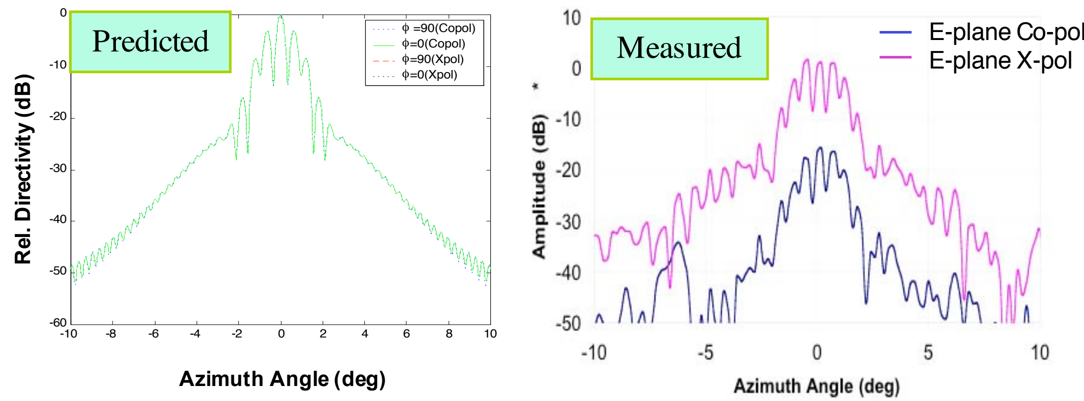


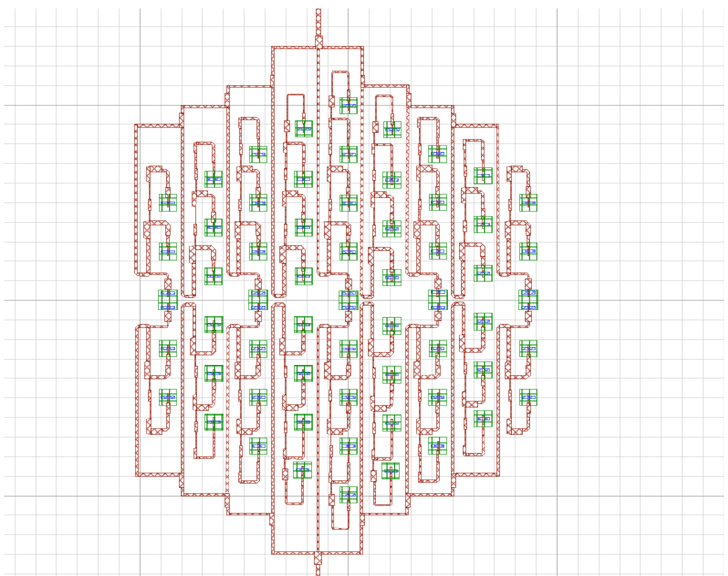
Spaceborne Atmospheric Radar Technology

GEO Hurricane Monitoring Radar:
Spherical Reflector Antenna Technology Prototype

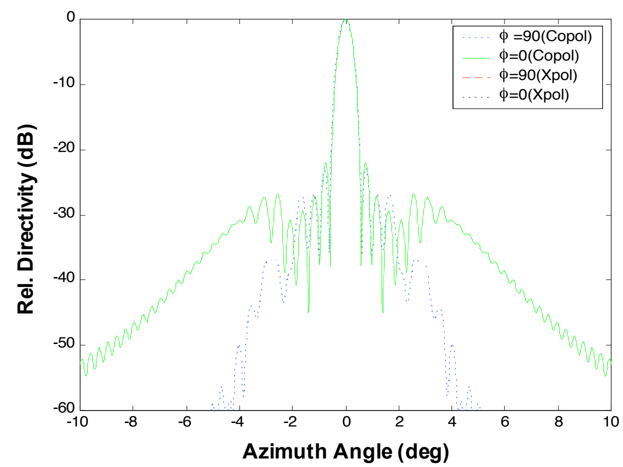
1.5-m spherical reflector w/ horn feed

Far-field patterns of 1.5-m reflector with horn feed





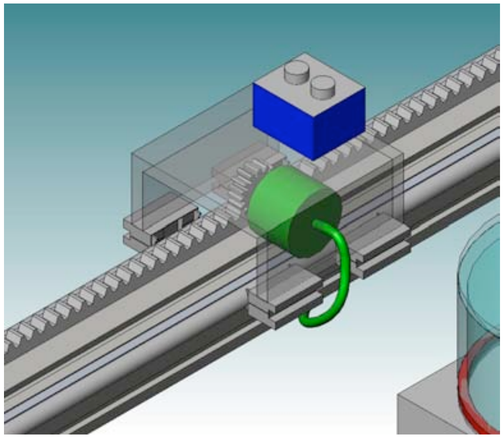
61-element array design



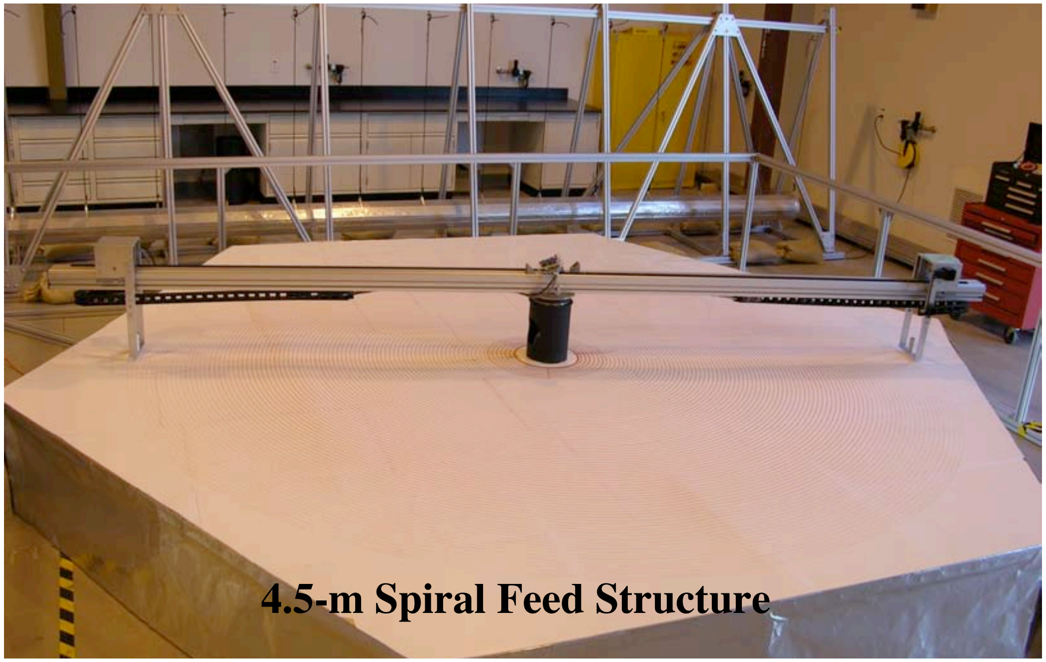
Predicted far-field patterns of 1.5-m reflector
With 61-element array

GEO Hurricane Monitoring Radar: Spiral Feed Structure Prototype (full-size)

- Approach:
  - Central rotating arm
  - Two linear motioned feed sets
- Design considerations:
  - Geometry of spiral
  - Trajectory velocity on spiral (Rotational and linear)
  - Acceleration of feed subsystem
  - Inertia and torque requirements for motor selection
  - Time vs. velocity for radial motion
  - Time vs. velocity for linear motion
  - Computer interface to motor controllers

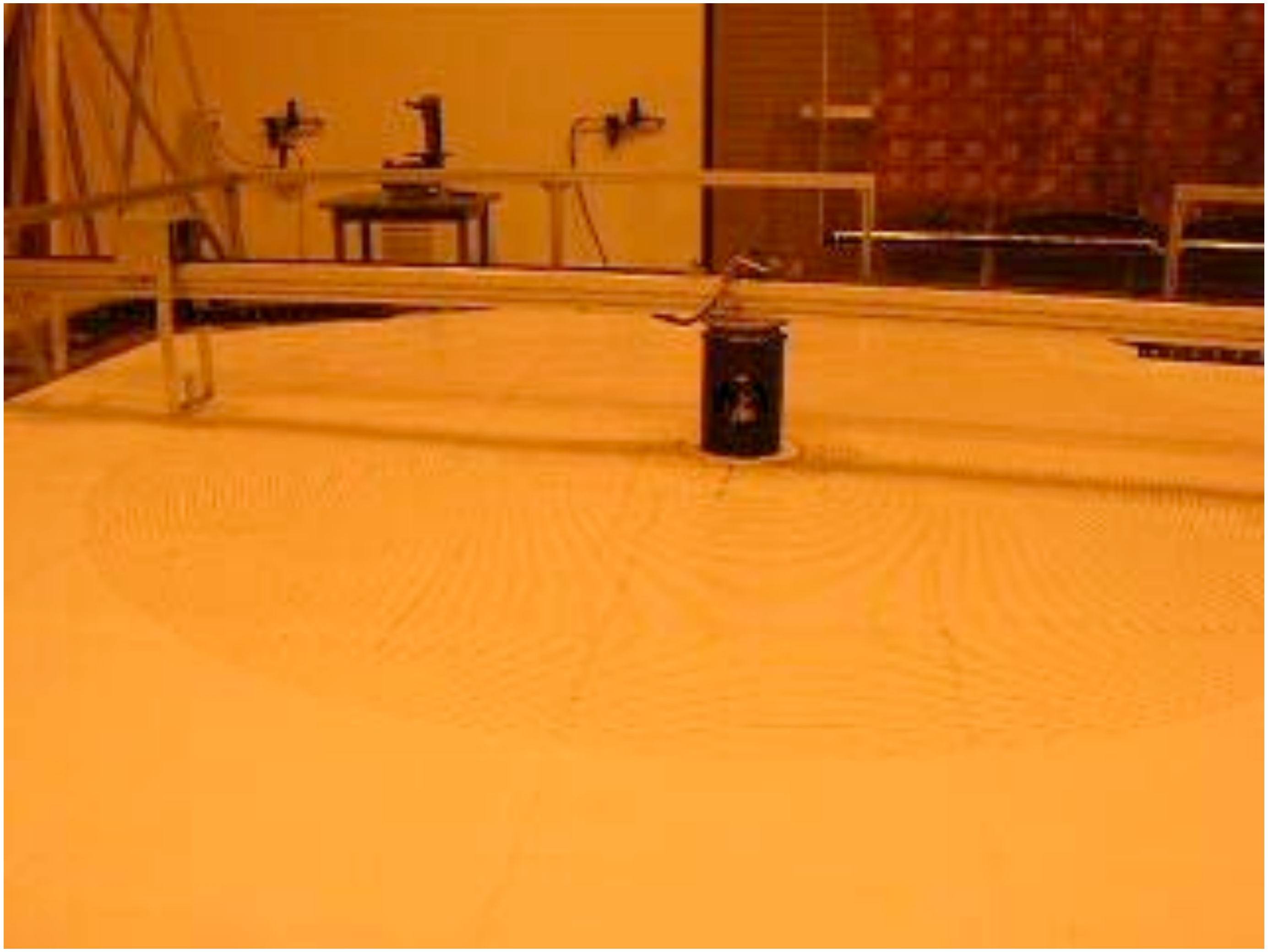


Linear-Motion Subassembly



4.5-m Spiral Feed Structure

GEO Hurricane Monitoring Radar:
Spiral Feed Structure Prototype - Spiral Motion



Summary & Remarks

- Radar technologies have reached to the point to support next-generation of spaceborne atmospheric measurements of rainfalls, storms and hurricanes
  - Focus on improved measurement accuracy, multi-parameter observations, mass/size/data reduction
  - Technologies can be infused incrementally

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  - ESTO - George Komar, Ken Anderson, Pepper Hartley, Tom Cwik, Loren Lemmerman, Dan Evans (Aerospace Corp)
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